



AFRL-AFOSR-VA-TR-2015-0230

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## High Performance Artificial Muscles Using Nanofiber and Hybrid Yarns

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UNIVERSITY OF TEXAS AT DALLAS

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07/14/2015  
Final Report

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Air Force Research Laboratory  
AF Office Of Scientific Research (AFOSR)/ RTD  
Arlington, Virginia 22203  
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# High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns

PI and co-PI: Ray H. Baughman and Michael Kozlov, University of Texas at Dallas

Grant FA9550-12-1-0211 (4/15/2012 – 4/14/2015)

## Motivation:

- ❖ Improved tensile and torsional actuators are needed for both micro and macro DoD applications.

## Objective:

- ❖ Develop new tensile and torsional artificial muscles that provide giant stroke, fast response, high force generation, and long cycle life. Optimize energy conversion efficiencies.

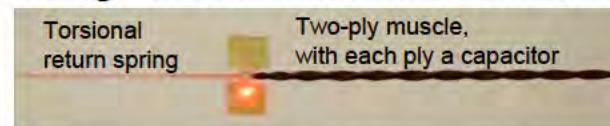
## Approaches:

- ❖ Thermally powered twisted guest@CNT yarn
- ❖ Sorptive-powered twisted guest@CNT yarn
- ❖ Coiled polymer muscles from fishing line
- ❖ Twisted dielectric polymer muscle fibers
- ❖ Coiled solid-state electrochemical muscles

## Recent Discoveries:

- ❖ Extended thermal hybrid yarn muscles to fast muscles powered by liquid sorption/desorption by silicone guest. Muscles provide 50% stroke, 31X the work/cycle of natural muscles, 1 Hz cycle rate, and an energy conversion efficiency of up to 16%. Demonstrated the use of these silicone@CNT yarn muscles as a control valve for liquid flow.

- ❖ Demonstrated electrically powered dielectric polymer fiber muscles that generated 4.5% tensile stroke, 800 rpm torsional rotation speed, and 100X higher torsional stroke than any prior-art muscle that is non-thermal and non-electrochemical. Muscles are based on our project-developed super-elastic CNT sheath/rubber core conducting fibers that enable 2470% stretch and giant twist insertion without conductance loss.



Torsional mechanism is new: tensile actuation drives torsional actuation

- ❖ Demonstrated all-solid-state electrically powered coiled CNT fiber muscles that generate 24% tensile stroke and provide 3.2% energy conversion efficiency (twice that of our CNT fiber muscles and 10X that of conducting polymer muscles). They maintain stroke without consuming significant energy.

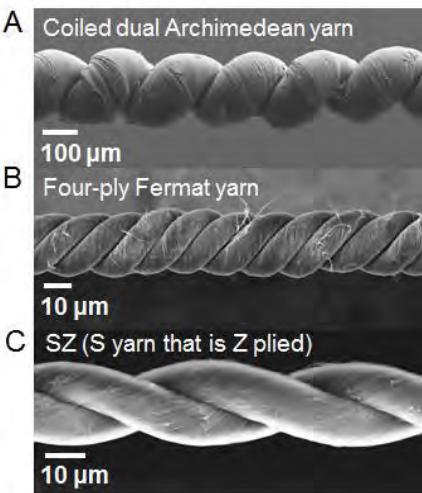


## Impacts:

Publication of polymer muscles (*Science*, 2014) generated TV, radio, and other world-wide news. In 2014, Lintec, Inc. started a laboratory close to UTD to commercialize CNT technology that we licensed and muscles technology for which we provided an option to license (world-wide patent nationalization resulted).

# Results Overview for the AFOSR Project (4/15/2012 -4/14/2015) on “High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns”

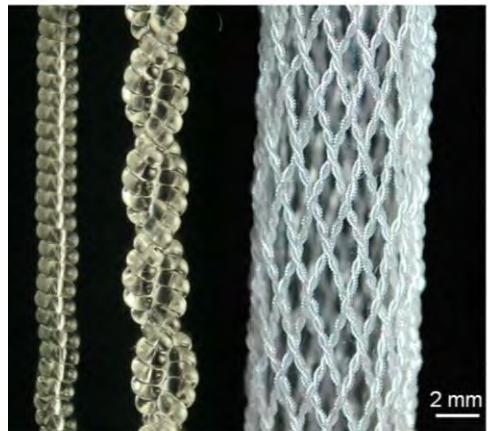
1. Work on twist-spun hybrid yarn muscles fast realized, patent-filed, and published in *Science* before 2012 ended. Recent results are in *Nature Comm.* (2014) & etc.



**Mechanism:** The volume change of guest in twisted or coiled CNT fiber drives thermal torsional and tensile actuation.

**Realized Performance:** (1) Average power density during muscle contraction of 28 kW/kg (85 times that for skeletal muscle). (2) Tensile contraction exceeding 50%. (3) Millions of reversible tensile actuation cycles at 1200 cycles/minute. (4) Torsional stroke ( $250^\circ/\text{mm}$ ) of 1000 times prior art. (5) Millions of torsional actuation cycles obtained, where a muscle spins a rotor at 11,500 rpm.

2. Above advance led to “Artificial Muscles From Fishing Line and Sewing Thread”, which was patent filed and then published in *Science* in 2014.



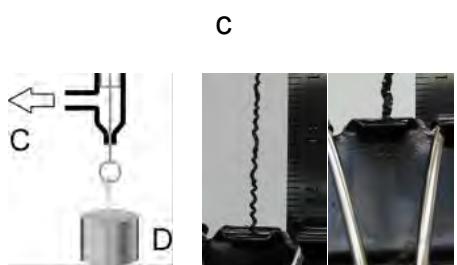
**Mechanism:** Thermally powered axial and radial dimension changes of twisted polymer fiber drives giant torsional actuation, as well as giant tensile stroke when the polymer fiber is coiled.

**Realized Performance:** (1) Higher contractile work capacity per cycle (2.5 kJ/kg) than expensive NiTi shape memory wires (0.93 kJ/kg). (2) Long cycle life, hysteresis-free performance, tensile strokes above 50%, and contractile power per weight 5X higher than for a car’s engine. (3) Rotor rotation above 80,000 rpm.

# CONTINUED: Results Overview for the AFOSR Project (4/15/2012 -4/14/2015) on “High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns”

## 3. New hybrid CNT yarn muscles driven by fast, liquid absorption/desorption (manuscript submitted and favorably reviewed by *Advanced Materials*)

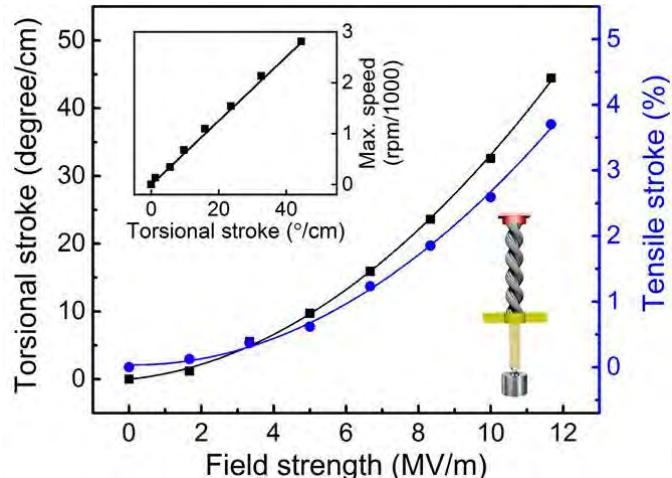
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**Mechanism:** Volume change of silicone rubber guest in coiled CNT fiber drives solvation-powered tensile actuation.

**Realized Performance:** (1) Provides up to 50% stroke to generate  $1.2 \text{ kJ kg}^{-1}$  of mechanical energy during contraction, which dwarfs the  $39 \text{ J kg}^{-1}$  of natural muscle. (2) One Hz cycle rate demonstrated. (3) Based on measured work/cycle and the calc. energy needed to recycle fluids, the energy conversions is 16%. (4) Use: Harvester of chemical energy of waste streams or as a powerful actuating sensor.

## 4. “Hierarchically Buckled Sheath-Core Fibers for Superelastic Electronics, Sensors, and Torsional Muscles” demonstrated and manuscript submitted to *Science*

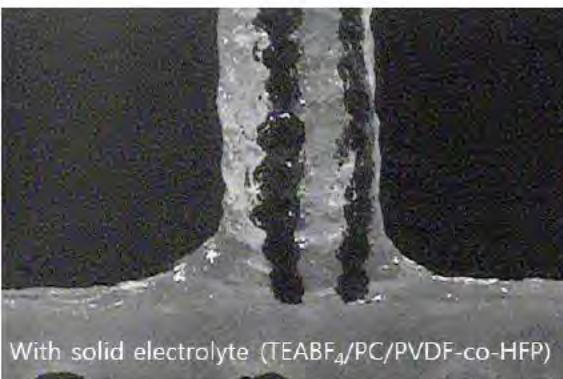
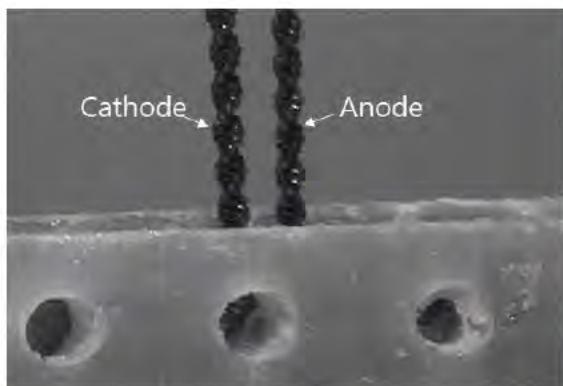
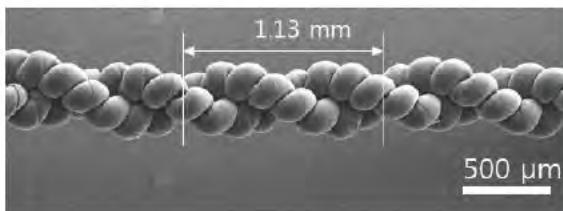


**Materials Strategy:** Novel 2-D periodically buckled CNT sheet sheaths on rubber fiber core are electrodes that enable giant stretch (up to 2470%) and giant twist insertion without significant conductance loss.

**Torsional Actuator Mechanism & Performance:** (1) Tensile actuation of rubber dielectric muscle layer in twisted fiber drives torsional actuation. (2) One hundred times higher torsional stroke per muscle length obtained than any prior art electrically powered muscle that does not suffer from the limitations of thermal and electrochemical muscles.

CONTINUED: Results Overview for the AFOSR Project (4/15/2012 -4/14/2015) on  
“High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns”

## 5. Yarn muscles converted to all-solid-state electrochemical muscles

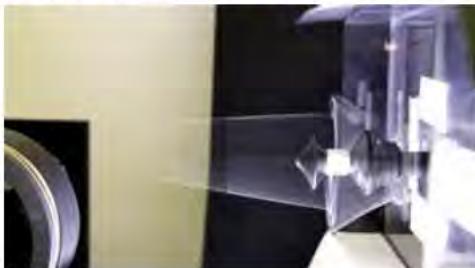


- ❖ In initial evaluations, obtained tensile strokes up to 24% and electrical-to-mechanical energy conversion efficiencies of up to 3.2%.
- ❖ These efficiencies already exceed the 1.5% that we obtain for pulse-actuated thermally-powered coiled muscles and the below 0.3% efficiencies of conducting polymer electrochemical actuators.
- ❖ In contrast with thermal muscles, the electrochemical muscles maintain stroke without significantly consuming energy.
- ❖ To increase efficiency and rate, we must (1) increase muscle work capacity per injected charge, (2) decrease hysteresis in charge/discharge, (3) decrease energy losses in the electrolyte, and (4) decrease inter-electrode distance.

# Additional results (2014) for the AFOSR Project on:

## “High Performance Artificial Muscles Using Twist-Spun Nanofiber and Hybrid Yarns”

Continuous polymer muscle fabrication demonstrated and upscaled in summer 2014



100 m of coiled nylon yarn muscle



Polymer muscles used to quickly lift and lower a heavy weight (Marcio)



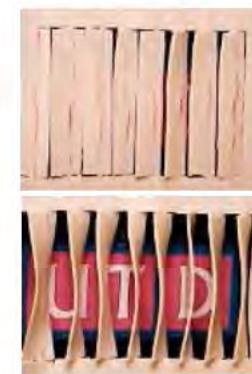
52 coiled, 65 lb test green-dyed polyethylene fishing lines provided the muscle, which was powered by alternating hot and cold water.

The diameter coiled muscle was 4 mm. The stroke was 5.5% as a 270 lb load was lifted. The maximum average power density realized for a polymer muscle during contraction was 7.1 horsepower/kg), 5X that of a car's engine.

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Demonstrated diverse morphing structures:

- ❖ Textiles that change porosity for possible applications in comfort-adjusting clothing (project-derived US patent filed in 2015).
- ❖ A thermally powered composites of coiled silicone@CNT muscles in a silicone matrix provided a peristaltic pump (left), coiled nylon muscles in silicone matrix thermally morphed by torsional rotation to open and close a window or vent (middle), and torsional electro-thermal actuation morphed the 45 cm diameter logo structure (right).



- ❖ While we still have many results that need more comprehensive theoretical insights, our present theoretical work has importantly guided experiments and is described in our project publications and supplemental materials.

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| <b>14. ABSTRACT</b><br><p>The objective of this program was to develop new tensile and torsional artificial muscles that provide giant stroke, fast response, high force generation, and long cycle life while optimizing energy conversion efficiencies. During the program we extended thermal hybrid yarn muscles to fast muscles powered by liquid sorption/desorption by silicone guest. These muscles provide 50% stroke, 31X the work/cycle of natural muscles, 1 Hz cycle rate, and an energy conversion efficiency of up to 16%. We used these silicone/CNT yarn muscles as a control valve for liquid flow. We also demonstrated electrically powered dielectric polymer fiber muscles that generate 4.5% tensile stroke, 800 rpm torsional rotation speed, and 100X higher torsional stroke than any prior-art muscle that is non-thermal and non-electrochemical. These muscles are based on our project-developed super-elastic CNT sheath/rubber core conducting fibers that enable 2470% stretch and giant twist insertion without conductance loss. We further demonstrated all-solid-state electrically powered coiled CNT fiber muscles that generate 24% tensile stroke and provide 3.2% energy conversion efficiency (twice that of our CNT fiber muscles and 10X that of conducting polymer muscles). They maintain stroke without consuming significant energy. The publication of Artificial Muscles From Fishing Line and Sewing Thread (Science, 2014) generated TV, radio, and other world-wide news. In 2014, Lintec, Inc. started a laboratory close to UTD to commercialize CNT technology that we licensed and muscles technology for which we provided an option to license (world-wide patent nationalization)</p> |  |  |
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**Principal Investigator Name**

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Ray H. Baughman

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**The AFOSR Program Manager currently assigned to the award**

Byung-Lip Lee

**Reporting Period Start Date**

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**Reporting Period End Date**

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**Abstract**

The objective of this program was to develop new textile and torsional artifical muscles that provide great stroke, fast response, high force generation, and long cycle life while optimizing energy conversion efficiency. During the program we extended thermal hybrid yarn muscles to fast muscles powered by quadrupole/desorption by silver cone guest. These muscles provide 50% stroke, 31X the work/cycle of natural muscles, 1 Hz cycle rate, and an energy conversion efficiency of up to 16%. We used these silver cone/CNT yarn muscles as a control variable for quadrupole flow. We also demonstrated electrically powered dielectric polymer fiber muscles that generate 4.5% tensile stroke, 800 rpm torsional rotation speed, and 100X higher torsional stroke than any prior-art muscle that is non-thermal and non-electrochemical. These muscles are based on our project-developed super-elastomeric CNT sheath/rubber core conducting fibers that enable 2470% stretch and greater twist insertion without conductance loss. We further demonstrated a solid-state electrically powered coated CNT fiber muscles that generate 24% tensile stroke and provide 3.2% energy conversion efficiency (twice that of our CNT fiber muscles and 10X that of competing polymers). They maintain a stroke without consuming significant energy. The publication of "Artificial Muscles From Fishing Line and Sewing Thread" (Science, 2014) generated TV, radio, and other world-wide news. In 2014, Lintec, Inc. started a laboratory close to UTD to commercialize CNT technology that we licensed and muscles technology for which we provided an option to license (worldwide patent rights on DISTRIBU

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### Archival Publications (published) during reporting period:

1. "Electrical power from nanotube and graphene electrochemical thermal energy harvesters" T. J. Kang, S. Fang, M. E. Kozlov, C. S. Hanes, N. L., Y. H. Kim, Y. Chen, and R. H. Baughman, *Advanced Functional Materials* 22, 477-489 (2012).
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8. "Increasing the efficiency of thermoacoustic carbon nanotube sound projectors", A. E. Adev, Y. N. Gartstein, R. H. Baughman, *Nanotechnology* 24, 235501 (11pp) (2013).
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**Changes in research objectives (if any):**

**Change in AFOSR Program Manager, if any:**

**Extensions granted or milestones slipped, if any:**

**AFOSR LRIR Number**

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**Research Objectives**

**Technical Summary**

**Funding Summary by Cost Category (by FY, \$K)**

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